61

Nuclear Plant Instrumentation and Control System Performance Monitoring

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INTRODUCTION

As most of the current generation of nuclear power plants have passed their mid-life, increased monitoring of their health is critical for their safe operation. This is especially true now that license renewal of nuclear power plants has accelerated, allowing some plants to operate up to 60 years or more. Furthermore, many utilities are maximizing their power output through upgrading their projects and retrofits. This puts additional demand and more stress on the plant equipment such as the instrumentation and control (I&C) systems and the reactor internal components, making them more vulnerable to the effects of aging, degradation, and failure. In the meantime, the nuclear power industry is working to reduce generation costs by adopting condition-based maintenance strategies and automation of testing activities.

These developments have stimulated great interest in on-line monitoring (OLM) technologies and new diagnostic and prognostic methods to anticipate, identify, and resolve equipment and process problems and ensure plant safety, efficiency, and immunity to accidents. The foundation for much of the required technologies has already been established through 40 years of research and development (R&D) efforts performed by numerous organizations, scientists, and engineers around the world. This chapter provides examples of these technologies and demonstrates how the gap between some of the more important R&D efforts and end users have been filled by providing the nuclear industry with the means to meet regulatory requirements, comply with technical specification provisions, or resolve operational and maintenance issues. In doing so, emphasis is placed on the development and implementation of noise analysis and OLM technologies for remote testing of the static and dynamic performance of process instrumentation sensors, while they remain installed and operational in nuclear power plants.

BACKGROUND

It has long been known that the condition of a nuclear power plant can be effectively monitored by the analysis of small fluctuations (noise) of the process variables around their stationary values. The technique is commonly referred to as *noise analysis*, *noise diagnostics*, or *reactor diagnostics*. The values of many important parameters, such as reactivity coefficients, vibration amplitudes, response times, and others, can be monitored. The abnormal state of the system is discovered either by a shift of these parameters into non-permitted regions, or by the appearance of a changed structure of the noise signatures (usually the frequency spectra), indicating an anomaly.

The advantage of the technique is that it is based on the measurement of process variables under operation without any external perturbation; hence, it is a non-intrusive technique that can be used under normal operations. Application of the method requires an understanding of the physical relationships between the various process variables, most notably the effect of the parameters of interest, such as temperature, pressure, or displacement on the measured quantity such as the fluctuations of the neutron flux. In possession of such relationships, the sought parameters can be extracted from the measured quantities by signal analysis methods. The majority of the applied research work in the area is constituted by physical modeling of noise phenomena and the elaboration of inversion methods for parameter estimation and anomaly detection. A brief description of the principles of noise analysis techniques is given at the beginning of the chapter, followed by examples of concrete applications implemented in nuclear power plants.

Historically, for various technical reasons, at the advent of these techniques, the analysis of test data was made off-line by evaluating analog recordings on tape recorders. However, with the developments in instrumentation, data acquisition, and computing power, on-line applications have become possible with dedicated equipment installed at the plants. Naturally, this incurs more stringent requirements from the utilities and regulatory bodies. The fundamentals of on-line monitoring, OLM, and the technical requirements for its implementation in nuclear power plants are summarized in this chapter.

One specialty of the noise analysis technique is that a change in the measured signal characteristics might be a result of either the change in the transfer properties of the system, or the change in the driving force, that is, the fluctuation of the parameter which induces the measured noise. Hence, setting a proper diagnosis requires deep expert knowledge in order to choose a proper model on which the diagnostic algorithm is based. In addition, there exists another ambiguity in the measurement, namely, that a change in the measured noise signature can be the result of deteriorating sensor characteristics. A very clear demonstration of this fact was provided by the Three Mile Island accident, where a substantial part of the accident sequence was due to a failed sensor, and the lack of the realization of this fact by the control room personnel. Sensor malfunction, or just de-calibration, can happen also under much less dramatic circumstances, by fouling, drift, response time degradation, and aging. As it turns out, noise analysis can be used even for sensor health analysis. That is, in the analysis, it is possible to differentiate between sensor degradation/failure and system malfunction/anomaly. Understandably, this requires the application of even more sophisticated methods/algorithms and deeper expert knowledge on both system and sensor characteristics.

GLOBAL POWER DEMAND AND ROLE OF NUCLEAR ENERGY

The demand for electrical power has been rising steadily, and the trend is expected to continue although it slowed a little in the years 2008 and 2009 due to the worldwide economic recession. More than 20% of the world population still lives without electricity and global efforts are underway to remedy this situation. On the other hand, the existing sources of carbon-free power generation are limited, unreliable, or inefficient. These factors and others have given a boost to public acceptance and economy of nuclear energy. Further, over the years between 1995 and 2005, nuclear energy gained substantial advantage over fossil fuel generation through better management of plant resources, reduction in duration of refueling outages, and gains in capacity factors. For example, in the year 2009, nuclear power plants in the United States operated at an average capacity factor of over 90% compared to less than about 70% a decade ago and the duration of refueling outages are now as little as 2 weeks, compared to several months a decade ago. The same success is experienced in other countries, reducing the generation costs below almost all other sources of power generation and making nuclear electricity economical and competitive. As importantly, the record of safety of nuclear power plants has also been excellent over the years between 1990 and 2010, with less than a handful of mishaps.

Today, there are about 440 nuclear power plants in operation around the world, producing over 15% of global electricity. Figure 61.1 shows the countries that generate electricity from nuclear energy and the share of the total electricity that comes from nuclear power in each country. The United States with 104 operating nuclear power plants and France with 58 nuclear power plants, are among the largest generators of nuclear energy. About 20% of U.S. electricity comes from nuclear power while the share of nuclear power is nearly 80% in France. France has started building new nuclear power plants (e.g., two new plants are under construction as of February 2010) and the U.S. is preparing to order its first nuclear power plant since the accident at the Three Mile Island Unit 2 site in 1979.

Absent from Figure 61.1, is the number of countries that have never had nuclear power sources but are actively seeking to employ nuclear energy for electricity production. For example, in January 2010, the United Arab Emirates (UAE) announced that it will buy a nuclear power plant from South

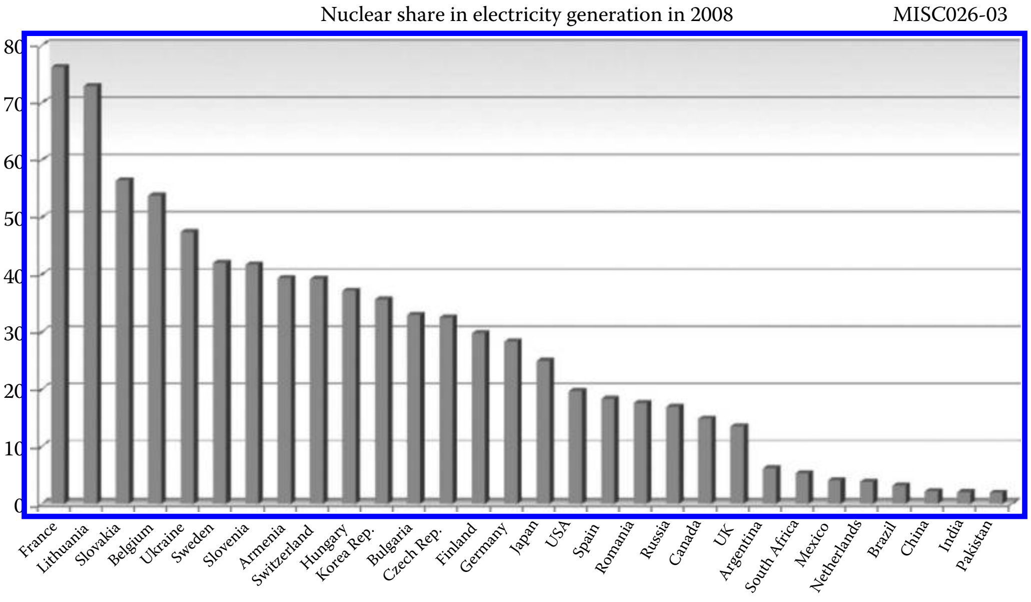

FIG. 61.1
Countries generating electricity from nuclear energy and share of total electricity using nuclear power in each country.

Korea. This is a very significant development for many reason, including (1) UAE has never had a nuclear power plant, and in spite of being in the Middle East with vast fossil fuel resources, it is adopting nuclear energy for the first time, testifying to the advantages of nuclear power as being an environmentally friendly, safe, reliable, and economical source of electricity generation, and (2) at this moment in time South Korea has never sold a nuclear power plant, yet it has been able to win over a number of established suppliers of nuclear technology. South Korea has been on the forefront of nuclear technology development over the last three decades; has continued to build nuclear power plants even when no other country was promoting the use of nuclear energy; and is now equipped and well qualified to compete with such suppliers as Westinghouse, General Electric, Areva, Mitsubishi, and others.

UAE is among a large number of countries that have announced plans to construct nuclear power plants for the first time. The list includes a number of African nations, more Middle Eastern countries, and others such as Poland and Turkey.

The success of nuclear energy in recent years is due to a number of factors besides those mentioned earlier. For example, optimized maintenance of plant equipment, incorporation of advanced technologies such as the testing and diagnostic methods, etc. are some of the major contributors to the recent success of the nuclear industry. A nuclear power plant using the technologies described in this chapter has seen estimated savings of nearly U.S.$20 million per each operating cycle of 18 months, increasing soon to U.S.$50 million per cycle upon full implementation of these technologies throughout the plant.

OLM FUNDAMENTALS AND BENEFITS

OLM Fundamentals

The term *on-line monitoring*, OLM, is used in this chapter to describe methods for evaluating the health and reliability of nuclear plant sensors, processes, and equipment from data acquired, while the plant is operating. Although OLM technologies typically apply to essentially all types of nuclear power reactors, in this chapter, pressurized water reactors (PWRs) are used as the reference plant for description of OLM implementation.

A PWR plant employs a number of sensors to measure the process parameters for controlling the plant and protection of its safety. Figure 61.2 shows a simplified diagram of a primary loop of a PWR plant and identifies the important sensors in this loop. Depending on the plant design and manufacturer, a PWR plant has two to four primary coolant loops with the exception of Russian PWRs (that are called VVERs or WWERs) which have up to six loops. The number of sensors that are typically found in the primary loop of a PWR plant is shown in Table 61.1. The normal output of these sensors can often be used to verify the performance of the sensors themselves and establish the health and condition of the plant.

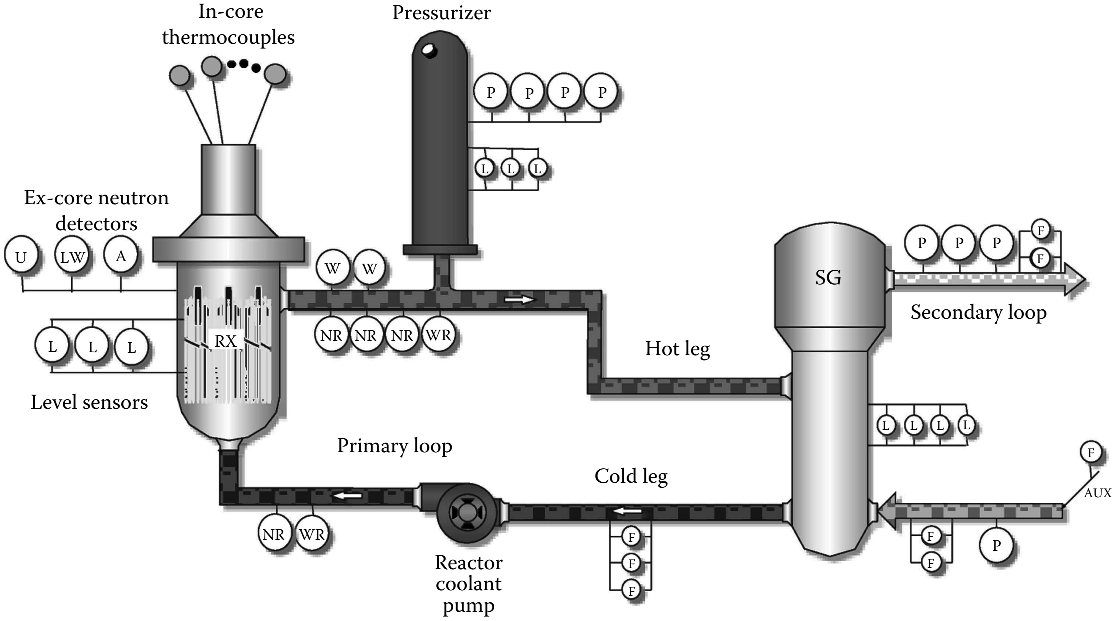

FIG. 61.2
Primary loop of a pressurized water reactor, PWR. A, average detector; F, flow transmitter; L, level transmitter; LW, lower detector, NR, narrow-range RTDs; P, pressure transmitter; RX, reactor; SG, steam generator; U, upper detector; W, wide-range pressure; WR, wide-range RTDs.

TABLE 61.1

Typical Population of Important Sensors in Pressurized Water Plants

Sensor	*Measurement*	*Typical Population in Reactor*
RTDs[a]	Temperature	16–60
CETs[b]	Temperature	50–100
Pressure transmitters[c]	Pressure, level, and flow	500–2500
Neutron detectors[d]	Neutron flux	10–20

[a] Resistance temperature detectors.

[b] Core-exit thermocouples.

[c] Including differential-pressure transmitters.

[d] Ex-core and some in-core neutron detectors.

In Figure 61.3, the output of a process sensor is shown as a function of time, during plant operation. Normally, while the plant is operating, the sensor's output will have a steady-state value corresponding to the process parameter indicated by the sensor. This steady-state value is often referred to as the *static* component or *DC value*. Figure 61.3 also shows a magnified portion of the sensor's output signal to illustrate that, in addition to the static components, a small fluctuating signal is naturally present on the sensor output. The fluctuating signal, which is known as the signal's *dynamic* component, stems from inherent fluctuations in the process parameter due to turbulence, random flux, random heat transfer, vibration, and other effects. The dynamic component is also referred to as the *AC signal* or the *noise output of the sensor*, and its analysis constitutes the field of *noise analysis,* which is the main focus of this chapter.

The static and dynamic components of the sensor output each contain different information about the process being measured, and as such, can be used for a number of OLM applications. For example, applications that monitor for gradual changes in the process over the fuel cycle, such as sensor calibration monitoring, make use of the static component. On the other hand, applications that monitor fast-changing events, such as core barrel motion, use the information in the dynamic component that provides signal bandwidth information. Figure 61.4 illustrates how existing data from process sensors is used to satisfy these applications. Note in this figure that the static data is analyzed using empirical and physical modeling, and averaging techniques involving multiple signals, while dynamic data analysis involves time domain and frequency domain analysis involving single signals or pairs of signals. For example, dynamic response time of a nuclear plant pressure transmitter is identified by fast fourier transform (FFT) of the noise signal. The FFT yields the auto power spectral density (APSD) of the noise data, from which the transmitter response time is calculated. In applications where pairs of signals are used (e.g., core barrel vibration measurements), the cross power spectral density (CPSD), phase, and coherence data are calculated to distinguish the vibration characteristics of various constituents of the reactor-internal.

The types of OLM applications in nuclear power plants are in large part determined by the sampling rates available for data acquisition. Static OLM applications, such as resistance temperature detector (RTD) cross-calibration and on-line calibration monitoring of pressure transmitters, typically require sampling rates up to 1 Hz, while dynamic OLM applications such as sensor response time testing uses data sampled in the 1 kHz range. Other OLM applications, such as vibration measurement of rotating equipment and loose parts monitoring, may use data sampled at up to 100 kHz. Figure 61.5 illustrates examples of OLM applications that can be used in nuclear power plants versus the range of data sampling frequency.

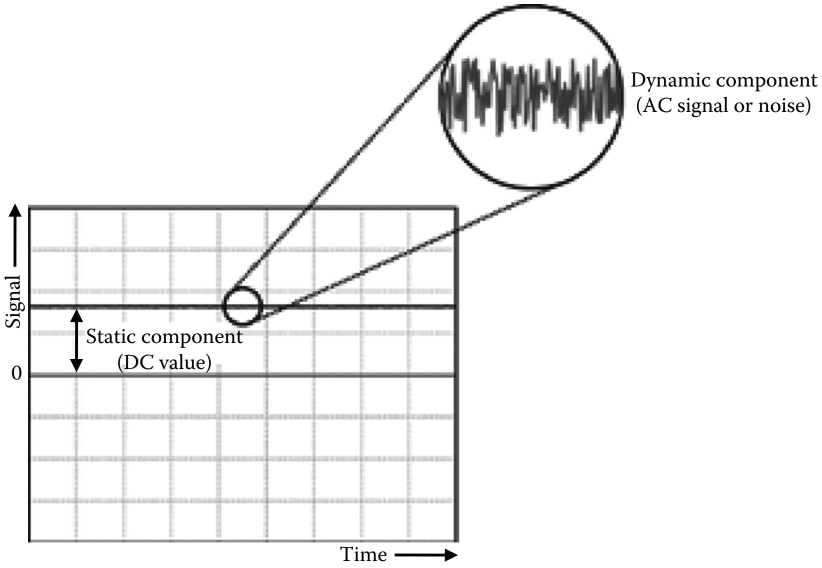

FIG. 61.3
Normal output of a process sensor with AC and DC components.

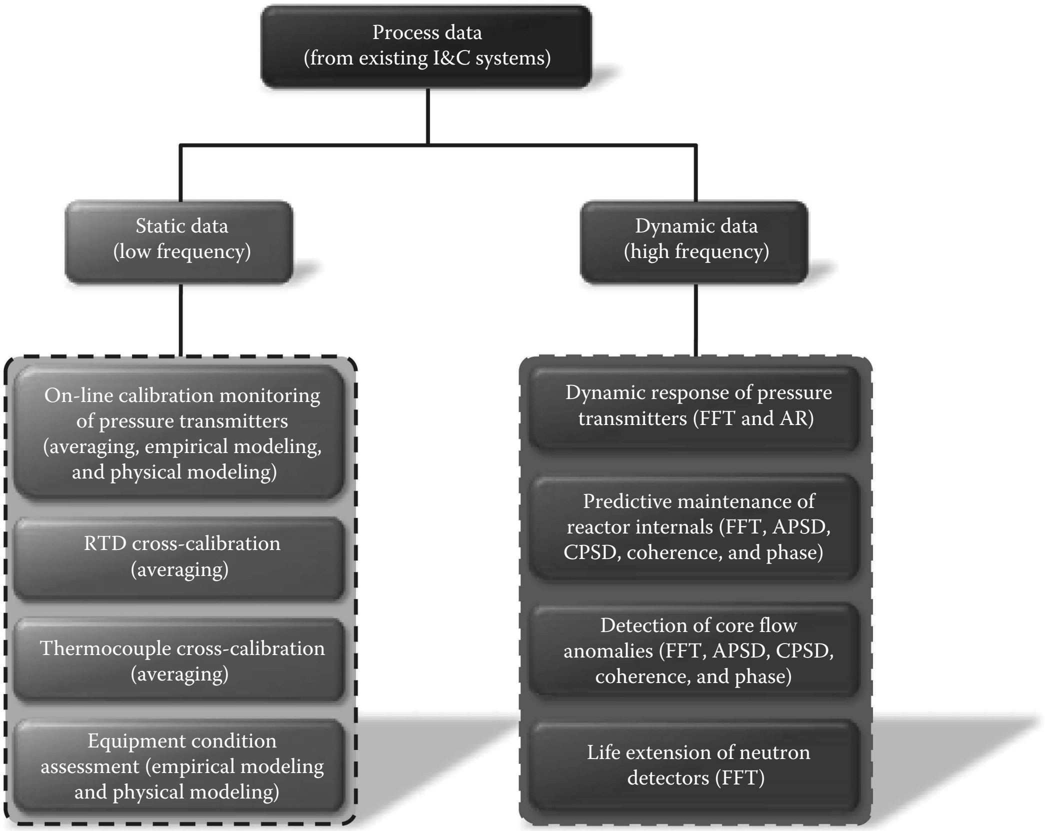
Process data
(from existing I&C systems)
Static data
(low frequency)
Dynamic data
(high frequency)
On-line calibration monitoring of pressure transmitters (averaging, empirical modeling, and physical modeling)
RTD cross-calibration (averaging)
Thermocouple cross-calibration (averaging)
Equipment condition assessment (empirical modeling and physical modeling)
Dynamic response of pressure transmitters (FFT and AR)
Predictive maintenance of reactor internals (FFT, APSD, CPSD, coherence, and phase)
Detection of core flow anomalies (FFT, APSD, CPSD, coherence, and phase)
Life extension of neutron detectors (FFT)

FIG. 61.4
On-line monitoring applications of static and dynamic data analysis. FFT, fast fourier transform; AR, autoregressive modeling; APSD, auto power spectral density, CPSD, cross power spectral density.

As noted in Figure 61.5, this chapter covers OLM applications that monitor I&C sensors such as temperature, pressure, level, flow, and neutron flux up to data sampling frequencies around 1 kHz. These types of sensors represent the majority of measurement devices in nuclear power plants, and thus plants can more readily stand to benefit from OLM applications that use them. Other OLM applications, such as vibration measurement of rotating equipment and loose parts monitoring, primarily relying on high-frequency acquisition of data from accelerometers, are not covered in this chapter

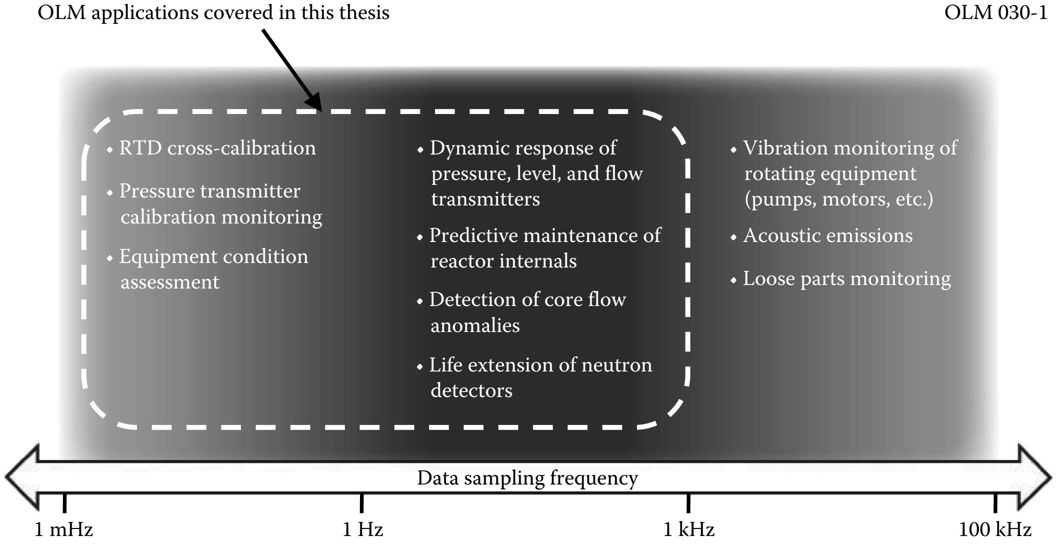
OLM applications covered in this thesis
OLM 030-1
• RTD cross-calibration
• Pressure transmitter calibration monitoring
• Equipment condition assessment
• Dynamic response of pressure, level, and flow transmitters
• Predictive maintenance of reactor internals
• Detection of core flow anomalies
• Life extension of neutron detectors
• Vibration monitoring of rotating equipment (pumps, motors, etc.)
• Acoustic emissions
• Loose parts monitoring
Data sampling frequency
1 mHz
1 Hz
1 kHz
100 kHz

FIG. 61.5
On-line monitoring applications versus sampling frequency.

as they are based on a separate set of sensors for data acquisition than existing process sensors.

OLM Benefits

Figure 61.6 shows essential cost components in power generation from fossil and nuclear fuels (excluding capital costs) in the United States. It is apparent that about 85% of the cost of electricity generation from fossil sources is in the fuel, while operations and maintenance (O&M) costs account for only about 15%. In contrast, nuclear energy generation costs are only about 30% in fuel and 70% in O&M. Since fuel costs are normally either constant or increase with time, there is little room for fossil power plants to reduce generation costs; while nuclear power plants can easily reduce generation costs by simply reducing O&M costs. This is one of the successful steps that the nuclear power industry took in the 1990s; contributing to the resurgence of nuclear energy and keeping the electricity prices down.

In reducing O&M costs, the nuclear industry has taken advantage of computer technologies to automate much of its testing and maintenance activities. In particular, the nuclear industry has begun to transition from the traditional time-directed, hands-on, and reactive maintenance procedures to condition-based, risk-informed, and automated maintenance strategies. The OLM technologies described in this chapter will help in this transition. In addition, these OLM technologies will be useful for the new generation of reactors and will help in contributing to the increased use of nuclear energy. This will provide direct benefits to the general public in terms of a carbon-free source of electricity generation, independence from fossil sources of energy, and compliance with efforts to help the environment.

OLM can fill a number of important needs of the nuclear industry such as continuous health assessment of plant equipment and processes, measurement of the dynamic performance of process instrumentation, in situ calibration verification of process instrumentation, detection of blockages, voids, and leaks in pressure sensing lines, detection of core flow anomalies, life extension of neutron detectors and other sensors, and measurement of the vibration of reactor internals. These applications can bring substantial benefits to nuclear power plants and will fulfill a number of important objectives. For example, continuous OLM assessment for real-time identification of a degrading instrument or process rather than waiting until the degradation results in a loss of function to a failure. This helps to focus the maintenance activities where they are most needed. It also helps in reduction of plant trips, optimization of maintenance schedules, and shorter plant outages.

Table 61.2 compares the benefits of current I&C maintenance practices with maintenance performed with the aid of OLM. It also shows the indirect benefits of OLM. Much of the indirect benefits arise from the reduction of unnecessary maintenance activities.

Motivation for OLM Development

Some of the material in this chapter has been drawn from the work of the author in nuclear power plants under commercial contracts. These contracts are issued by nuclear utilities to fulfill a variety of needs such as I&C performance measurements to comply with nuclear regulatory regulations, predictive maintenance, aging management of reactor internals and other components, troubleshooting to identify, and resolve equipment or process problems such as flow anomalies, and increased monitoring to comply with

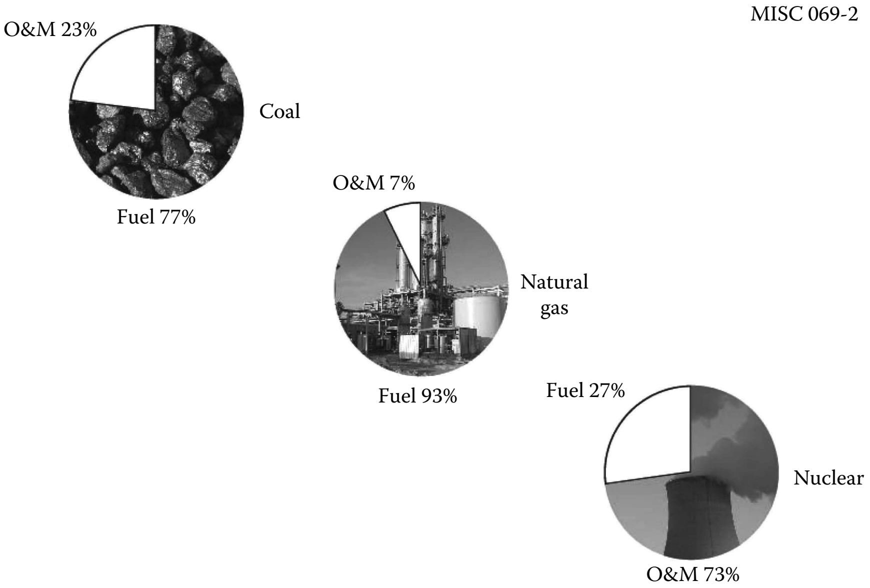

FIG. 61.6
Cost of fuel in electricity generation in the United States compared to operations and maintenance costs (capital costs are not included).

TABLE 61.2
Benefits of On-Line Monitoring

Conventional Maintenance Practice	*Maintenance by On-Line Monitoring*
Performed manually	Automated
Requires access to equipment	Performed remotely and hands-off
Performed occasionally	Performed continuously
Detects problems after they have occurred	Detects problems as they occur
Some maintenance can be performed only when the plant is at shutdown	Most maintenance can be performed during plant operation
Environmental and process condition effects are not typically included	Environmental and process condition effects are included
Process monitoring is not possible	Process monitoring is possible
Indirect Benefits	
Optimization of maintenance tasks	
Reduced outage time	
Labor cost savings (I&C technicians, operations, utility support and supervisors, quality assurance/quality control [QA/QC] personnel, health physics [HP] personnel, administrative personnel)	
ALARA savings (as low as reasonably achievable)	
Trip reduction	
Reduced potential for damage to equipment	
Other benefits (e.g., cost and time of dress-out to enter radiation controlled zone and Low-Level Waste [LLW] cost reduction)	

life extension objectives. For example, there are regulatory requirements for testing the response times of safety-related temperature and pressure sensors in plants. According to these requirements, utilities must measure the "in-service" response time of their safety-related sensors. This requirement is met in nuclear power plants using the noise analysis technique. In addition, with the noise analysis, sensor response time measurements are performed remotely from the control room area while the plant is on-line. These measurements do not require the sensors to be disconnected from the plant instrumentation or removed from service for the tests. That is, the tests are passive and do not cause any disturbance to plant operation. This saves test time and helps to reduce radiation exposure to the test personnel who would otherwise have to enter the reactor containment to make the response time measurements. As importantly, in the case of pressure sensors, the noise analysis technique provides the response time of the entire pressure sensing system including the sensing lines which bring the pressure signal from the process to the sensor. As a result, any blockages, voids, or leaks that can affect the dynamic response of a pressure transmitter are detected by the noise analysis techniques.

The success of the noise analysis in nuclear power plants has stimulated the industry to examine the feasibility of implementing on-line condition monitoring systems incorporating the noise analysis in both the current and next generation of nuclear reactors for dynamic testing of sensors, measurement of vibration of reactor internals, and a variety of diagnostic applications. The system will also, and as importantly, provide the capability to verify the calibration of pressure, level, and flow transmitters as well as RTDs and thermocouples. The foundation for development of the system and its design details and implementation requirements are presented later in the section dedicated to OLM System for Nuclear Power Plants. The system will have built-in signal validation, noise analysis, and OLM algorithms for nuclear power plants to check for (1) calibration and response time of process instruments, (2) identify sensing line blockages, (3) monitor the reactor coolant flow, and (4) alert the reactor operator of any excessive vibration of reactor internals.

OLM technologies provide plants with the information needed to evaluate I&C sensors with applications focused on identifying drifting instruments, alerting plant personnel of unusual process conditions, and predicting impending failures of plant equipment. In addition, OLM technologies can be used to improve the efficiency of operating nuclear power plants. For example, nuclear power plants are required to calibrate important I&C instruments once every fuel cycle. This requirement dates back to almost 50 years when commercial nuclear power plants were first licensed to begin operations. Based on the calibration data accumulated over these 40 years, it has been determined that the calibration of some instruments, such as pressure transmitters, do not drift enough to warrant calibrating all transmitters as often as once every fuel cycle. OLM allows calibration efforts to be focused on the instruments that have drifted out of tolerance, thereby saving plants a significant amount of the time and manpower resources that are traditionally involved in periodic calibrations. For more information on calibrations, refer to Chapter 7.

To date, several technologies have been developed for implementing OLM in nuclear power plants. However, installing an OLM system, collecting and organizing the data, and performing precise analysis of the data are not straightforward. The operating experience from successful implementations and the requirements for implementation found in this chapter are intended to provide the necessary guidance for plant implementation of OLM in both the existing fleet and the next generation of nuclear reactors.

OLM IMPLEMENTATION IN NUCLEAR POWER PLANTS

The material in this section originates from experimental and theoretical research activities leading to practical (real world) measurements and diagnostics performed over the last 30 years in more than 100 nuclear power plants in the United States, Europe, and Asia. Much of these measurements and diagnostics were performed in support of I&C system maintenance and investigation of anomalies in the primary and secondary systems. A summary of these activities is presented in this section.

It should be pointed out here that the terms "pressure sensor" and "pressure transmitter" used in this chapter are synonymous and refer to the equipment that measure pressure, level, and flow. Often, the term *sensor* is used in nuclear power plants to refer to temperature measurement equipment such as thermocouples and RTDs, the term *transmitter* is used to refer to equipment that measures pressure and differential pressure, and the term *detector* is used to refer to the equipment that measures neutron flux.

On-Line Detection of Sensing Line Blockages

Chief among applications of noise analysis in nuclear power plants is the detection of sensing line blockages. Sensing lines (also called *impulse lines*) are small diameter tubes which bring the pressure signal from the process to the pressure sensor. Depending on the application and the type of plant, pressure sensing lines can be as long as 300 m or as short as 10 m. They have isolation valves, root valves, and bends along their length making them susceptible to blockages from residues in the reactor coolant, failure of isolation valves, and other problems. Sensing line blockages are a recurring problem in PWRs, boiling water reactors (BWRs), and essentially all water-cooled nuclear power plants. It is an inherent phenomenon which causes the sensing lines of nuclear plant pressure transmitters to clog up with sludge, boron, magnetite, and other contaminants. Typically, nuclear plants purge the important sensing lines with nitrogen or back fill the lines periodically to clear any blockages. This procedure is, of course, time consuming and radiation intensive, and more importantly, not always effective in eliminating blockages. Furthermore, except with noise analysis, there is no way to know ahead of time which sensing lines may be blocked. Also, without the noise analysis technique, it is not possible after purging or back filling a sensing line to verify that the line has been cleared.

The degree of increase in the dynamic response depends on the "compliance" of the pressure transmitter. Compliance is a pressure transmitter design parameter which relates to the physical displacement of the sensing element of the transmitter per unit of input pressure. Some transmitters such as those with sensing elements made of "bellows" have a large compliance and are therefore affected strongly by sensing line blockages. On the other hand, transmitters with sensing elements made of stiff diaphragms have smaller compliances and are therefore less affected by sensing line blockages.

The effect of compliance on dynamic response of a pressure transmitter was uncovered in a research project performed by the author for the U.S. Nuclear Regulatory Commission (NRC) in the early 1990s [1]. The goal of the project was to characterize the effects of normal aging on performance of nuclear plant pressure transmitter. Figure 61.7 shows an example of the results of this research project, illustrating the effect of compliance on response time of representative nuclear-grade pressure transmitters from three manufacturers (Table 61.3): Barton, Foxboro, and Rosemount. This data is from the laboratory tests measuring the response time of the transmitters using a pressure ramp signal.

Response Time Testing of Pressure Transmitters

Pressure, level, and flow transmitters in nuclear power plants behave like filters to the natural plant fluctuations that are presented to their inputs. That is, if one assumes that the input to the transmitter exhibits wide-band frequency characteristics (typically the case for nuclear power plant fluctuations), information about the sensor itself can be inferred by measuring the transmitter output. This is the basis of the

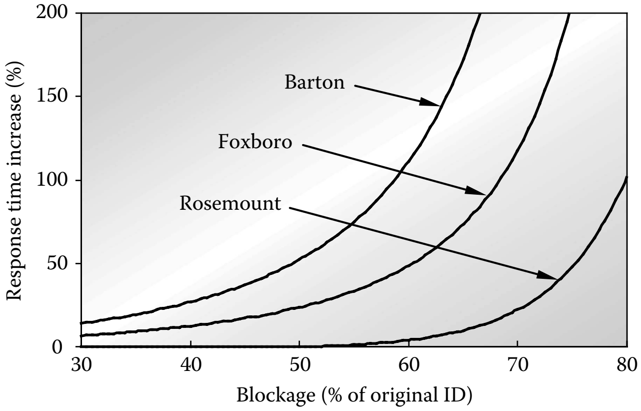

FIG. 61.7
Research results on the effect of sensing line blockages on response time of nuclear plant pressure transmitters.

TABLE 61.3
Compliance of Nuclear-Grade Pressure Transmitters from Selected Manufacturers

Manufacturer	*Model Number*	*Compliance (cm^3/Bar)*
Barton	764	9.51
Foxboro	E13DM	0.12
Rosemount	1153RC7	0.01

noise analysis technique to determine the dynamic response of pressure, level, and flow transmitters [2].

Dynamic response analysis is performed in the frequency domain and/or time domain, and is based on the assumption that the dynamic characteristics of the transmitters are linear and the input noise signal (i.e., the process fluctuations) has proper spectral characteristics. Frequency domain and time domain analyses are two different methods for response time determination of transmitters, and it is usually helpful to analyze the data with both methods and average the results excluding any outliers.

In frequency domain analysis, the APSD of the signal is first generated usually using a FFT algorithm. After the APSD is obtained, a mathematical function (model) that is appropriate for the transmitter under test is fit to the APSD to yield the model parameters that are then used to calculate the dynamic response of the transmitter. The dynamic response of the transmitter can then be analyzed to determine the transmitter's response time in situ. Figure 61.8 shows an example of process noise that enters a pressure transmitter and is subsequently filtered by the transmitter. The response time of the transmitter can be inferred from the APSD with the proper analysis tools.

Under normal plant conditions, the APSDs of nuclear plant pressure transmitters have characteristics shapes that can be baselined and compared with the APSDs of similar transmitters operating under the same process conditions. Figure 61.9 shows examples of a few typical nuclear plant APSDs. The APSDs shown are for steam generator level, reactor water clean-up flow, and pressurizer pressure transmitters.

On-Line Calibration Monitoring of Pressure Transmitters

On-line calibration monitoring refers to the monitoring of the normal output of nuclear plant pressure transmitters during plant operation and comparing the data with an estimate of the process parameter that the transmitter is measuring. With this method, transmitter outputs are monitored during process operation to detect drifts. If a drift is identified and is significant, the transmitter is scheduled for a calibration during an ensuing outage. On the other hand, if the transmitter drift is insignificant, no calibration is typically performed for as long as 8 years. This 8-year period is based on a 2-year operating cycle and a redundancy level of four transmitters. In this application, OLM is not a substitute for traditional calibration of pressure transmitters; rather, it is a means for determining when to schedule a traditional calibration for a pressure transmitter.

Reviews of calibration histories of process instruments in nuclear power plants have shown that high-quality instruments—such as the nuclear-grade pressure transmitters—typically maintain their calibration for more than a fuel cycle of about 2 years and do not, therefore, need to be calibrated as often [3,4].

At most plants, the plant computer contains all the data that is needed to verify the calibration of pressure transmitters. This includes data from plant startup and shutdown periods to verify the calibration of instruments over their operating range.

The validity of the OLM approach to verify the calibration of nuclear plant pressure transmitters was researched by the author under the auspices of the NRC. This project involved theoretical work as well as laboratory experiments and in-plant trials. The results are documented in a comprehensive NRC report [3].

To perform on-line calibration monitoring, the output of redundant sensors is averaged, and the average value is called the *process estimate*. This process estimate is then used as a reference to determine the deviation of each sensor from the average of the redundant sensors and identify the outliers. For non-redundant sensors, a reference value cannot obviously be determined by averaging. Therefore, if there is not enough instrument redundancy, the process estimate for calibration monitoring is determined by analytical modeling of the process. Both empirical and physical modeling techniques are used in this application; although, empirical models are preferred due to their adaptability to various processes and different operational envelopes. In particular, empirical modeling techniques involving neural networks were researched by the author for on-line calibration monitoring applications in nuclear power plants as documented in NUREG/CR-6343. Although successful, neural networks are not currently favored for this application by the nuclear industry due to difficulties in determining the uncertainty of their results. As such, other methods have been developed for this application.

In Situ Cross Calibration of Temperature Sensors

PWR plants often employ a number of RTDs to measure the fluid temperature in the reactor coolant system. The

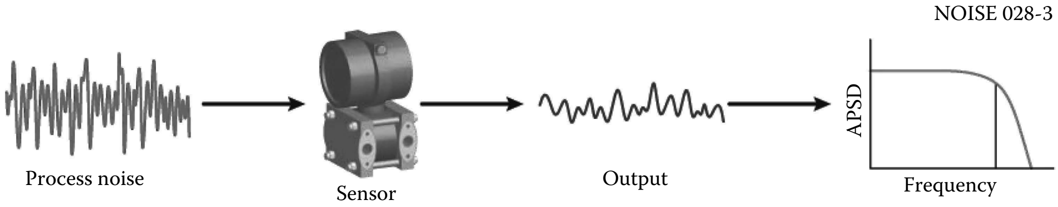

FIG. 61.8
Example of a pressure transmitter filtering the process noise.

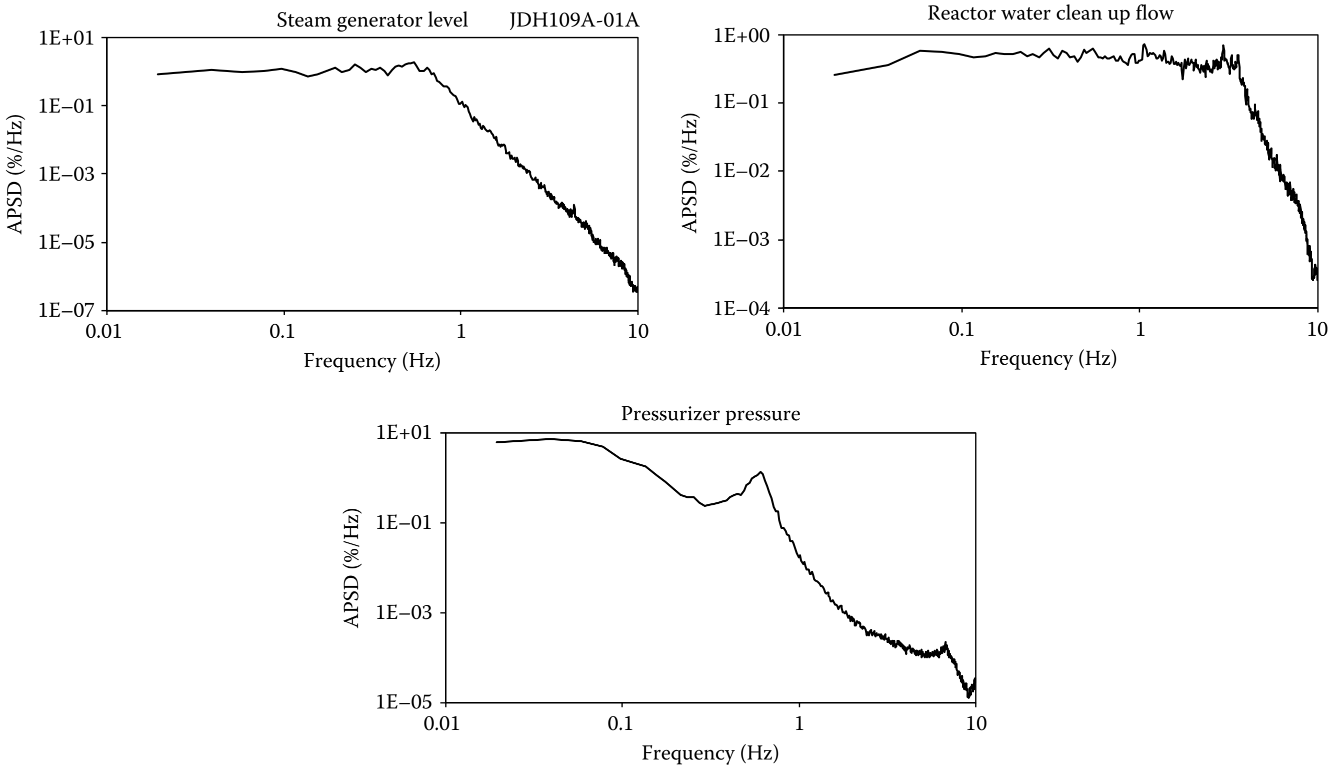

FIG. 61.9
Examples of auto power spectral densities of nuclear plant pressure transmitters.

temperatures measured by the RTDs are used by the plant operators for process control and to assess the operational status and safety of the plant. As such, the calibrations of the RTDs are normally evaluated at least once every refueling cycle. Each RTD must meet specific accuracy requirements for the plant to continue to produce power according to its design specifications. There are also core exit thermocouples (CETs) in PWRs to provide an additional means of monitoring the reactor coolant temperature. Typically, a PWR plant has 20–40 RTDs and 50 CETs. The accuracy of CETs is not as important as RTDs because CETs are used mostly for temperature monitoring. Nevertheless, CETs are sometimes cross calibrated against RTDs to ensure that their outputs are reliable.

In each loop of a PWR plant and for each core quadrant, redundant RTDs and CETs are used to minimize the probability of failure of any one RTD or CET having a serious effect on the operator's ability to safely and efficiently operate the plant. This redundancy of temperature sensors is the basis for a method of evaluating the calibration of RTDs and CETs called *cross calibration*. In cross calibration, redundant temperature measurements are averaged to produce an estimate of the true process temperature. The result of the averaging is referred to as the *process estimate*. The measurements of each individual RTD and CET are then subtracted from the process estimate to produce the cross calibration results in terms of the deviation of each RTD from the average of all redundant RTDs (less any outliers). If the deviations from the process estimate of an RTD or CET are within acceptable limits, the sensor is considered in calibration. However, if the deviation exceeds the acceptance limits, the sensor is considered out of calibration, and its use for plant operation is evaluated.

Traditionally, cross calibration data has been acquired using data acquisition equipment that is connected temporarily to test points in the plant instrumentation cabinets. The traditional cross calibration method, while highly accurate, causes the plant to lose indication when the data is being acquired and costs the plant time during shutdown and/or startup to defeat and restore the temperature indications. Now, with new and more advanced plant computers, RTD and CET measurements can be collected in the plant computer which provides a centralized location for monitoring and storing the measurements. Using on-line data from the plant computer for cross calibration can save plants startup and shutdown time, while producing results comparable to the traditional method.

Fluid Flow Monitoring

In a PWR plant, 50 thermocouples are located on the top of the core. These thermocouples are normally used to monitor the reactor coolant's temperature at the output of the core. They can also be used in conjunction with the ex-core neutron detectors to monitor for flow through the reactor system. More specifically, by cross correlating signals from the ex-core neutron detectors and CETs, it is possible to identify the time that it takes for the reactor coolant to travel between the physical location of the neutron detectors and the thermocouple (Figure 61.10). The result, referred to as *transit time* (τ), can be used with core geometric data to evaluate the reactor coolant's flow through the system, identify flow anomalies, detect flow blockages, and perform a variety of other diagnostics. The same concept has been used for measurement of primary coolant flow in PWR plants. The procedure is referred to as Transit Time Flow Measurement (TTFM).

Furthermore, in a PWR plant, Nitrogen-16 (N-16) is produced by a fast neutron induced reaction with oxygen in the primary coolant water. The N-16 is a radioisotope of nitrogen and has a half-life of 7.35 s. In its decay back to oxygen, it emits high energy gamma rays. As the N-16 is transported by the primary coolant, these gamma rays can be detected by radiation monitors (N-16 detectors) that are installed on the primary loop hot leg piping (Figure 61.11). The coolant flow can then be determined by measuring fluctuations in the intensity of the N-16 gamma radiation and analyzing with the cross-correlation method.

An alternative method to the cross correlation technique for determination of transit time is to analyze the data in the frequency domain. The Fourier transform of the detector data can be used to determine the phase spectrum of the data in the frequency domain. The phase spectrum can then be used to determine the transit time (Figure 61.12).

Life Extension of Neutron Detectors

Aging management of neutron detectors is somewhat dependent upon the detector manufacturer and the nuclear plant strategy for performance verification of nuclear instrumentation systems. Some manufacturers recommend periodic replacement of the detectors as often as once every 5 years and other manufacturers state that neutron detectors can be used for as long as 40 years if they are in good working condition. In the latter case, manufacturers sometime recommend cable testing and static and/or dynamic performance monitoring as a means of verifying that the neutron detectors are in good working condition.

The dynamic response of neutron detectors can be monitored using the noise analysis techniques. In fact, response time testing as a means of trending the performance of

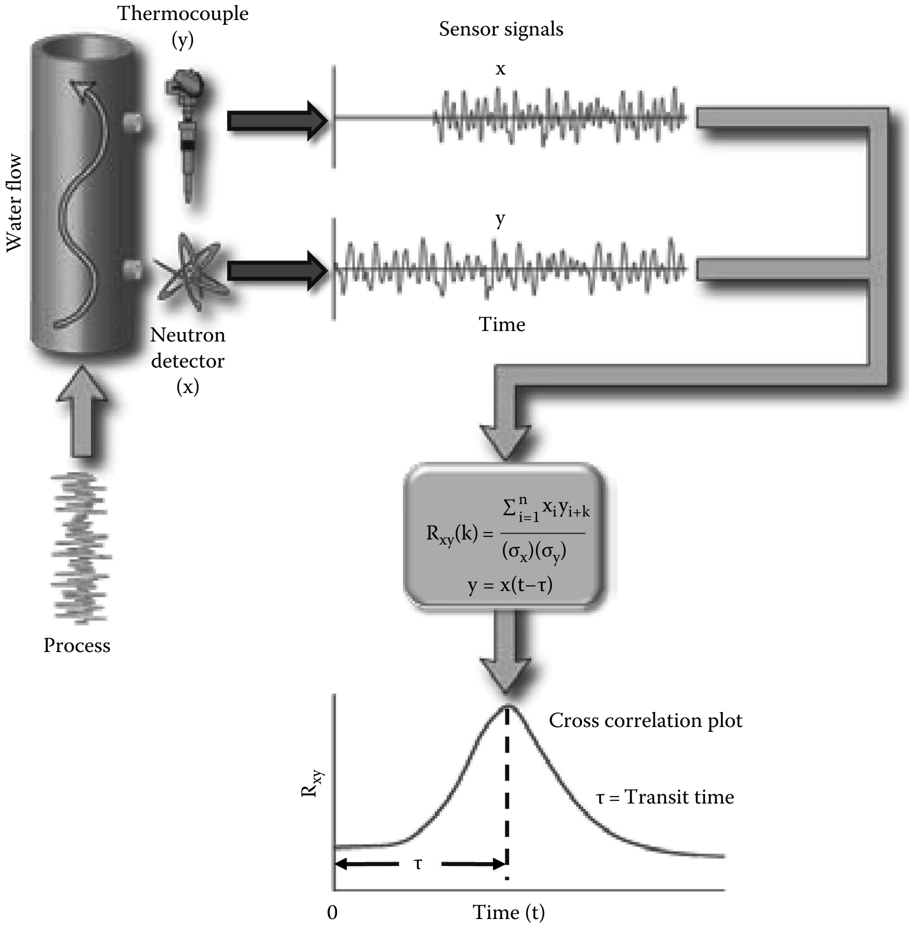

FIG. 61.10
Illustration of cross-correlation principle involving a neutron detector and a core-exit thermocouple to determine transit time.

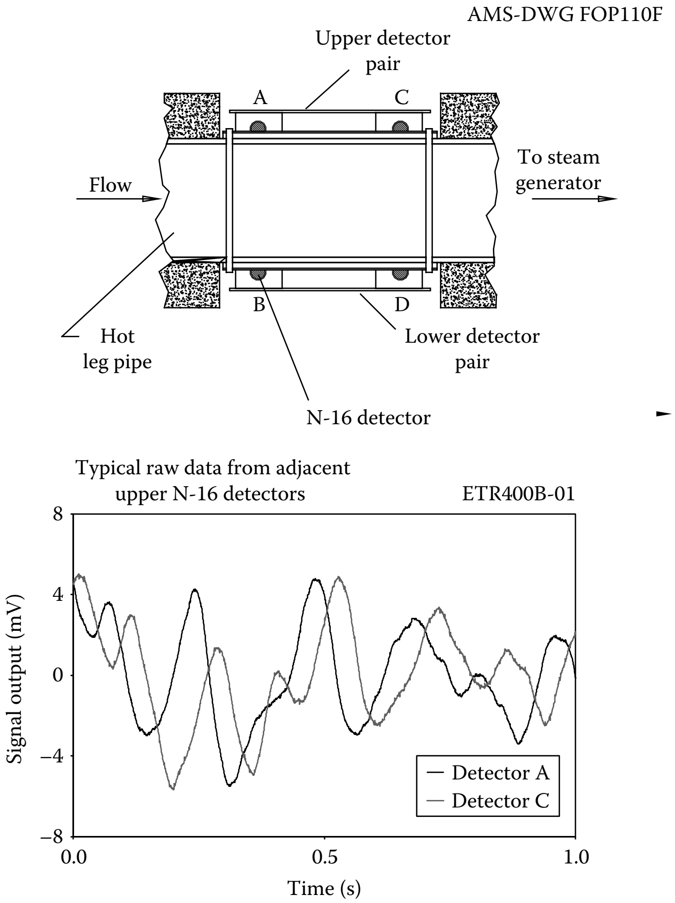

FIG. 61.11
Detector placement and a typical noise data record.

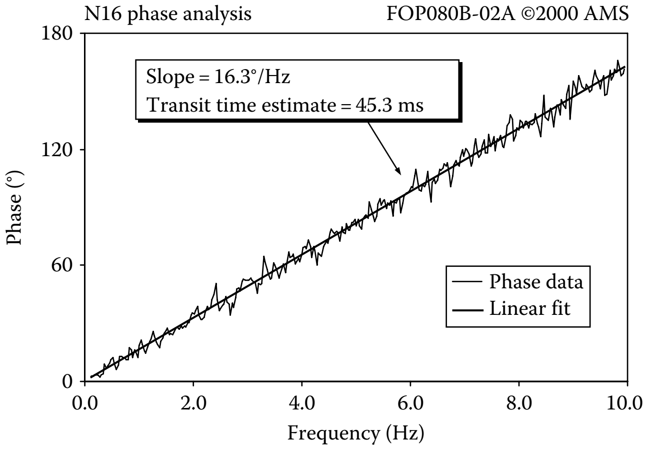

FIG. 61.12
Frequency domain phase analysis to determine transit time.

neutron detectors in nuclear power plants goes back nearly 30 years. Results of such tests performed by the author in a U.S. nuclear power plant are shown in Table 61.4 for four ex-core neutron detectors, each with an upper and a lower sensor. As demonstrated by these results, the response time of the detectors increases during the first two decades and then stabilizes. This is expected of neutron detectors, as well as other sensors.

In addition to trending response times, the noise output of neutron detectors can be examined for signs of other problems in the nuclear instrumentation circuit, such as cable and connector anomalies. Figure 61.13 shows the APSD of a neutron detector before and after the onset of a cable degradation problem. In this case, analysis of the APSD reveals a difference in the neutron detector dynamic response due to an increase in cable capacitance [5]. Continuous monitoring of neutron detectors can reveal problems in the neutron detector circuit so that plant personnel can schedule maintenance accordingly.

OLM SYSTEMS FOR NUCLEAR POWER PLANTS

An OLM system is made up of a data acquisition module involving hardware and software and a data processing module involving software implemented on fast computers. The system can be built into the design of new plants or deployed as an add-on feature to the existing generation of plants. Figure 61.14 shows a block diagram of this system.

TABLE 61.4

Results of Trending Dynamic Response of Neutron Detectors in a Nuclear Power Plant

		Response Time vs. Years in Service			
	Tag Number	10 Years	20 Years	24 Years	30 Years
1	NI 41 Upper	0.61	0.77	0.60	0.72
2	NI 42 Lower	0.61	0.79	0.64	0.71
3	NI 42 Upper	0.62	1.00	1.11	0.90
4	NI 42 Lower	0.57	1.03	1.25	0.93
5	NI 43 Upper	0.64	0.97	1.04	0.82
6	NI 43 Lower	0.54	1.06	1.10	0.78
7	NI 44 Upper	0.73	0.88	0.67	0.85
8	NI 44 Lower	0.59	0.86	0.68	0.72
Average response time (s)		0.61	0.92	0.89	0.80

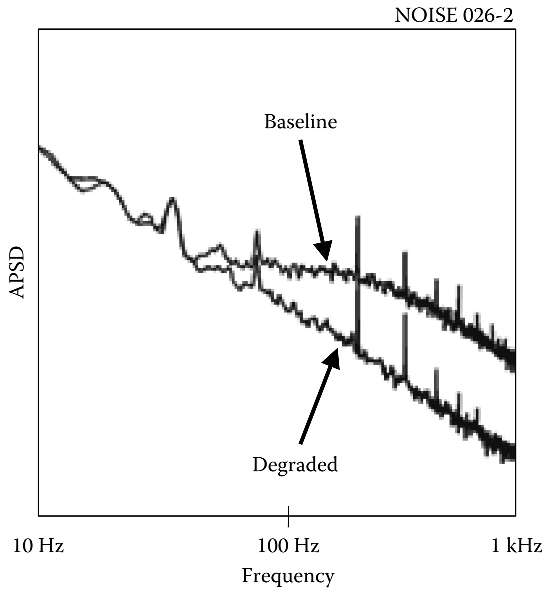

FIG. 61.13

Auto power spectral density of a neutron detector showing degradation due to an increase in cable capacitance.

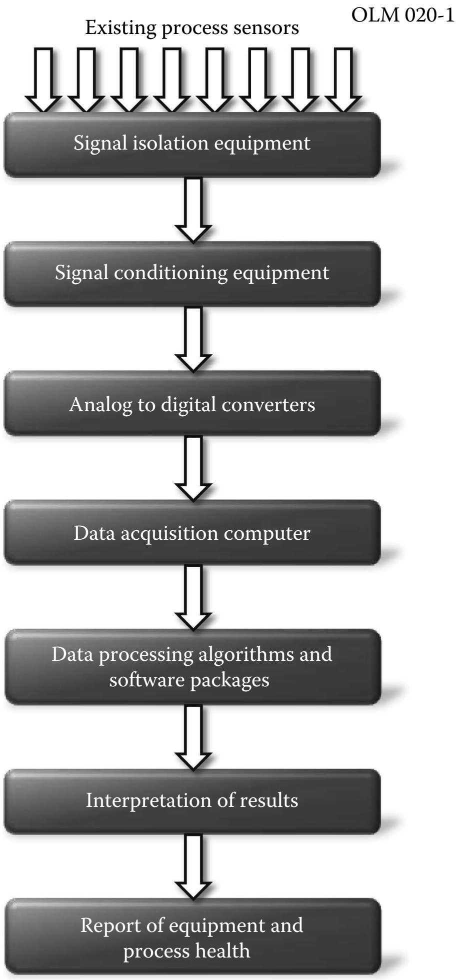
OLM 020-1
Existing process sensors
Signal isolation equipment
Signal conditioning equipment
Analog to digital converters
Data acquisition computer
Data processing algorithms and software packages
Interpretation of results
Report of equipment and process health

FIG. 61.14

Block diagram of on-line monitoring system.

A fundamental requirement for an OLM system is a fast data acquisition module. In the current generation of nuclear power plants, data from process sensors is normally sampled by the plant computer at rates of one sample per second or slower. This is adequate for applications such as calibration monitoring, but not for dynamic analysis. For analysis of dynamic signals, at least 100–1000 samples per second are normally required. In the new generation of nuclear power plants, this requirement can be accommodated simply by bringing the data into the plant computer through a fast analog-to-digital (A/D) converter and providing adequate storage to save the data for subsequent retrieval and analysis. However, in the existing generation of reactors, it is not simple to retrofit the plant with a fast data acquisition system and new storage provisions. In fact, even recent digital retrofits in nuclear power plants have not provided the necessary means for fast data collection and storage. As such, in the current generation of nuclear power plants, a separate data acquisition system must be installed for collection of dynamic data.

Figure 61.15 shows a block diagram of a dedicated data acquisition system for OLM. The system not only acquires data for OLM applications but also takes calibration signals and simulated faults to verify its own operation and calibration. In its signal conditioning module, it contains gain amplifiers, DC offset circuits, and anti-aliasing filters to separate the AC component of a sensor output from its DC component.

The system shown in Figure 61.16 was designed and developed by the author and installed for a period of about 3 years in the early 1990s at the McGuire nuclear power station in the United States. The work was done under an R&D contract funded by the NRC [3]. This system was used to provide data for development and validation of the first versions of OLM algorithms and software packages that the author helped develop.

OLM data, whether it is acquired using a dedicated data acquisition system or from a plant computer, must first be qualified or validated. This can be accomplished automatically using algorithms embedded in software packages that perform statistical calculations on the raw data. More specifically, the mean value, variance, skewness, and kurtosis of the raw data is calculated and trended. The results of these calculations are then used to identify and remove anomalous data records. For example, the skewness for a normal data record is expected to be near zero, and its kurtosis should be equal to one. This and similar other criteria are used to distinguish between the normal data records and the outliers.

For analysis of OLM data, there are two sets of techniques: one for analysis of low-frequency data for such applications

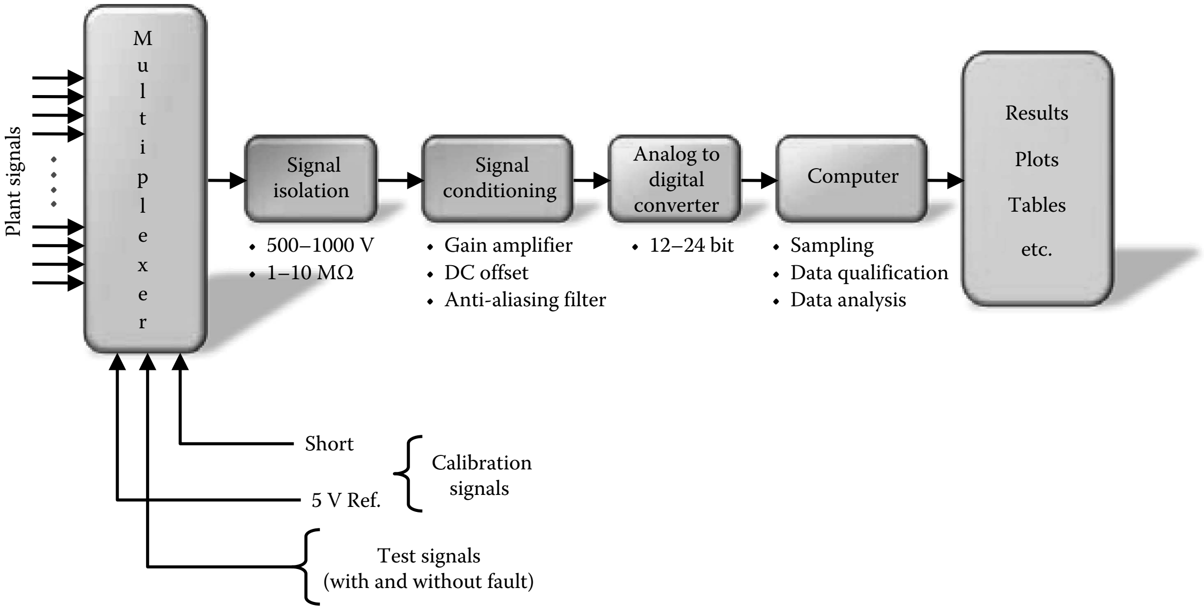

FIG. 61.15
Dedicated data acquisition system for on-line monitoring.

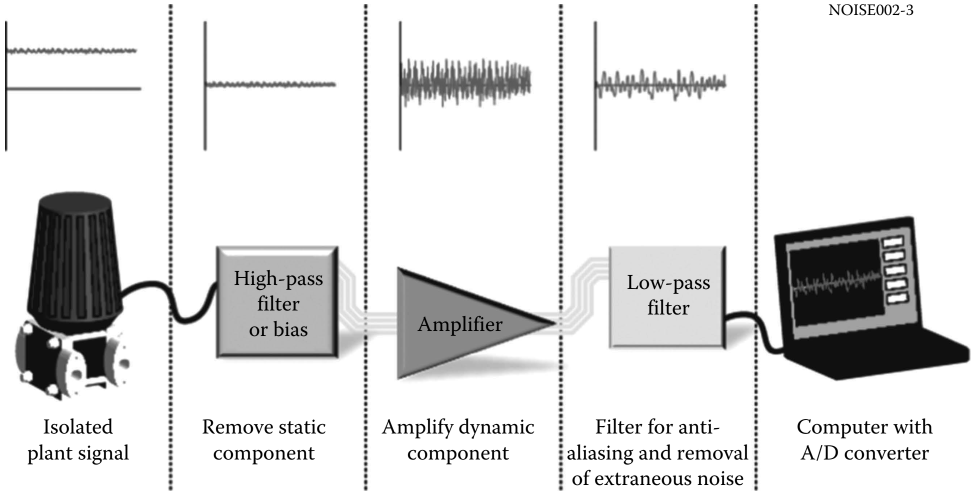
NOISE002-3
High-pass filter or bias
Amplifier
Low-pass filter
Isolated plant signal
Remove static component
Amplify dynamic component
Filter for anti-aliasing and removal of extraneous noise
Computer with A/D converter

FIG. 61.16
Data flow in separating the AC component of a sensor output from its DC component.

TABLE 61.5
Key Requirements for On-Line Monitoring Data Acquisition Hardware

OLM Data Acquisition Requirements		
	Minimum	*Optimum*
Sampling rates (Hz)	100	1000
Input impedance (MΩ)	1	100
Electrical isolation (V)	500	1000
Input channels	16	32
A/D resolution	12 bit	24 bit
Sampling time	1 h	Continuous

as detection of drift in the output of process transmitters and equipment condition monitoring and another for analysis of high-frequency data for sensor response time testing, diagnostics of dynamic effects such as vibration of reactor internals, cross correlation of signal pairs for flow monitoring, and detection of flow blockages and flow anomalies. For low-frequency data analysis, averaging techniques are typically used for redundant sensors; empirical and physical modeling techniques are used for non-redundant sensors.

In designing a data acquisition system for OLM implementation in nuclear power plants—whether it is for the new generation or the old generation of plants—it is important for the data acquisition system to have ample electrical isolation and very high input impedance. The input impedance must remain high even if the power to the equipment is lost. Table 61.5 lists some of the key requirements for an OLM data acquisition system.

Today, even some of the best data acquisition systems that are on the market can load down the plant circuits and cause plant trips. As such, nuclear power plants are very cautious about impedance and isolation requirements. The minimum input impedance for the data acquisition system that is allowed in nuclear power plants is typically about 1 MΩ and the minimum electrical isolation is 500 V. A more desirable system will have an input impedance of 1000 MΩ and will provide 1000 V of electric isolation.

AVAILABLE RESOURCES AND THE SOFTWARE

A prerequisite for OLM implementation in nuclear power plants is a means for collection of data from plant sensors. This is available in most plants in terms of commercial software packages such as the "PI System" which is the product of a company by the name of OSI Soft and "eDNA software" which is the product of a company by the name of Instep Software. These software packages are installed on the plant network to collect, historize, and store the data from hundreds of sensors, I&C systems, and other sources. To historize the data, limits are defined as to which data points or data records may be kept and those that can be discarded. For example, if the value of the process parameters remains within a certain band, instead of keeping all the points, the system keeps one point to represent the value of the process parameter. For OLM purposes, however, the historizing option shall either be disabled or its limits widened to keep as much of the data as possible.

For data analysis, only proprietary software packages are available for the use of the nuclear power industry. These packages use a variety of data analysis techniques such as FFT and autoregressive modeling (AR) to perform dynamic analysis and averaging and empirical modeling for analysis of static data. An example of results of dynamic data analysis is sensor response time and an example of results of static data analysis is instrument drift. In empirical modeling methods for data analysis, a variety of algorithms and software packages are used incorporating neural networks, kernel regression, fuzzy data clustering, or a combination of these and other techniques.

SUMMARY AND OUTLOOK

Over the last 40 years, an array of techniques has been developed for equipment and process condition monitoring. These techniques have been implemented in nuclear power plants mostly on an "as-needed" basis rather than for routine condition monitoring applications. Now, with the advent of fast data acquisition technologies and proliferation of computers and advanced data processing algorithms and software packages, condition monitoring is performed routinely and efficiently.

This chapter provided a review of a class of condition monitoring technologies which depend on data from existing process sensors during all modes of plant operation including start up, normal operating periods, and shutdown conditions. The data may be sampled continuously or periodically depending on the application. The steady-state (or DC) component of the data is analyzed to identify slowly developing anomalies such as calibration changes in process sensors. The fluctuating (or AC) component of the data is analyzed to determine such parameters as response time of pressure sensors or measure the vibrational characteristics of reactor internals, check for blockages within the reactor coolant system, identify flow anomalies, and provide other diagnostics. The latter is referred to as *noise analysis* which has been the main focus of this chapter.

The AC and DC data acquisition and signal processing techniques described in this chapter can be integrated together to provide an on-line monitoring system for nuclear power plants. A design for this system was introduced in this chapter together with the requirements for its implementation. It is envisioned that such OLM systems will be built into the design of the next generation of reactors to provide automated measurements, condition monitoring, and diagnostics to contribute to optimized maintenance of the plant. As for the current generation of reactors, they would be retrofitted with OLM systems as utilities begin to appreciate their benefits, and the regulators realize the added benefits of OLM to the safety of nuclear reactors.

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